The Development of a Biofuels Engine Testing Facility

D. Palmer[1], L. Lorenzen[1] and S.J. van der Spuy[2]
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A biofuel-specific engine test cell was designed and implemented for future testing of the performance differences between biodiesel and mineral diesel. The test cell was tested and adjusted manually until stable conditions were reached, after which an automated test was implemented. Tests were run on the following fuels: ultra low sulphur diesel (used as the base line with a maximum sulphur content of 50 ppm); B5, B10, B15 and B50 biodiesel-diesel blends and pure biodiesel (B100).

The calorific value of biodiesel was calculated using the calorific value of mineral diesel and the pure biodiesel test data. This was compared to the calorie bomb test which proved that the test cell has been calibrated correctly and provides accurate measurements. The performance of biodiesel and mineral diesel are similar despite higher fuel consumption rates for biodiesel as it has a lower calorific value. It can be concluded that the test cell performed to the required specification and that biodiesel, in terms of performance, can be considered a suitable replacement for mineral diesel without the need for engine modifications. Long term reliability tests must still be performed on biodiesel.

Nomenclature

AVL	Test equipment manufacturer
A/D	Analogue to digital
D/A	Digital to analogue
Bxx	Blend ratio of biodiesel to mineral diesel
ETA	Engine test automation software
PC	Personal computer
PPM	Parts per million
PLC	Programmable logic controller
rpm	Revolutions per minute
SANS	South African National Standards
ULSD	Ultra low sulphur diesel

1. Introduction

The use of biodiesel blends is becoming more prevalent as there is greater awareness about the environmental impact, depleting mineral oil reserves and dependency on the crude oil supply. Biodiesel can be manufactured from various raw materials, such as fish or vegetable oil. The production of biodiesel from the various raw materials lends itself to small, localised plants, making quality control, testing and distribution of the biodiesel difficult. The chemical composition of biodiesel can be tested in a laboratory, although more in-depth research is required to determine the combustion parameters.

An autonomous engine test cell has been developed to test the performance characteristics of biodiesel. The design was completed in three phases: hardware (dynamometer and test bed); electronics (PLC and sensors) and software to control the test cell. From the test results conclusions are drawn about the engine performance differences between mineral diesel and a specific test sample of biodiesel as well as assessing the accuracy of the test cell.

2. Literature Review: Biodiesel and its Combustion Characteristics

There are approximately 350 oil bearing crops that can be used for biodiesel production, of which only a handful can be considered a viable replacement for mineral diesel, mainly because the others are not produced in sufficient quantities[1]. A percentage replacement of mineral diesel with biodiesel can reduce a countries dependency on mineral imports and stimulate the economy through job creation. The food market, however, is in direct competition with the fuel market, which leads to an increase in prices and possible food shortages because the fuel market is willing to pay a premium for the vegetable oils.

Biodiesel's properties are dependant on the raw material and processes used for manufacture. The properties, despite the influencing factors, are similar to diesel and can thus be substituted without engine modifications. The specifications controlling biodiesel's properties vary widely between countries, due to an absence of an international standard[2].

When biodiesel is injected into the cylinder the spray penetration and pattern are the first in a sequence of parameters to be affected in a standard diesel compression ignition engine. The primary factors affecting the spray are the spray angle, volatility, surface tension and viscosity. The spray angle of biodiesel is narrowed to about half that of mineral diesel[3] and the higher viscosity and surface tension combined with a lower volatility lead to reduced atomisation. Poor atomisation causes larger droplet formation and a longer ignition delay but can be improved by higher injection pressures, assistant swirl and a smaller orifice diameter.

Apart from being a renewable energy source, biodiesel is a cleaner burning fuel than mineral diesel as it results in lower emissions. One possible exception is that nitrogen oxides (NO_x) emissions are in some cases adversely affected, which can be attributed to the small advance in fuel injection timing needed due to the different biodiesel combustion characteristics[4]. Carbon monoxide, hydro carbons and smoke are also reduced, with the latter being reduced as a result of the additional oxygen content in biodiesel[5].

The power developed by an engine running on biodiesel or its blends is similar to that of mineral diesel, while the exhaust

1 Department of Process Engineering, University of Stellenbosch, 7602, Matieland, South Africa

2 MSAIMechE, Department of Mechanical and Mechatronic Engineering, University of Stellenbosch, 7602, Matieland, South Africa
E-mail: sjvdspuy@sun.ac.za

gas and lubricating oil temperatures are lower[5] with no reported problems of hot or cold starting. The thermal efficiency remains similar, although the brake specific fuel consumption increases because of the lower calorific value of the biodiesel. Blending of biodiesel with mineral diesel, such as B20 (20 % biodiesel + 80 % mineral diesel) can reduce emissions without affecting the fuel combustion or injection properties.

3. Experimental Setup

3.1 Test facility layout

The test facility has a traditional layout, with the control room located next to the test cell with a window for visual monitoring (figure 1). The control room houses the PC and the rack with the controllers with the engine and measuring equipment isolated from the operator in the test cell (figure 2).

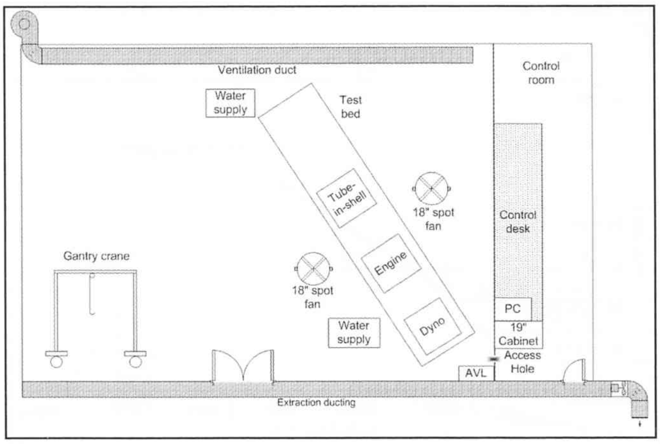

Figure 1: Diagrammatical layout of the biofuels testing facility

The major components in the test cell are shown and labelled in figure 2:

(1) The tube-in-shell heat exchanger allows engine coolant to be added in a closed loop system while being connected to the test facility water supply, rather than connecting the engine directly to the water supply.
(2) Toyota® 2C turbo diesel: The 2 litre indirect injection engine with mechanical fuel pump was chosen for its commissioning simplicity.
(3) The shaft protector houses a cardan shaft connecting the engine to the dynamometer.
(4) A Schenck® D360 hydraulic dynamometer is used to dissipate the work done by the engine to the water from cooling supply.
(5) AVL® 7030 dynamic fuel balance. The fuel consumption (given in grams per second) is calculated by weighing a vessel filled with fuel at regular intervals.
(6) Honeywell® 3-way mixing valve to control the water temperature at the inlet side of the engine.
(7) Floor spot fans are used to eliminate localised hot spots and aid ventilation in the test cell.

3.2 Automation and control

A prerequisite for the test cell stipulated that testing was to be performed autonomously. The automation was done with a PC, programmable logic controller (PLC shown in figure 2) and ETA software. The PLC is used to sample the readings from the various sensors, such as thermocouple and pressure transducers and acts as an A/D or D/A card (for example, the PC to Schenck controller). The PLC firmware was programmed in RSLogix. The throttle is operated by means of a servo motor with a PLC driven pulse width modulator.

The ETA software package allows the user interface to be tailored for a specific application. For this application the interface is shown in figure 3. The performance curve was also programmed into ETA with readings to be taking at 250 rpm intervals. After the initial setup, the operator only needs to start the test, after which a performance curve will be generated, the engine allowed to cool and then switched off automatically.

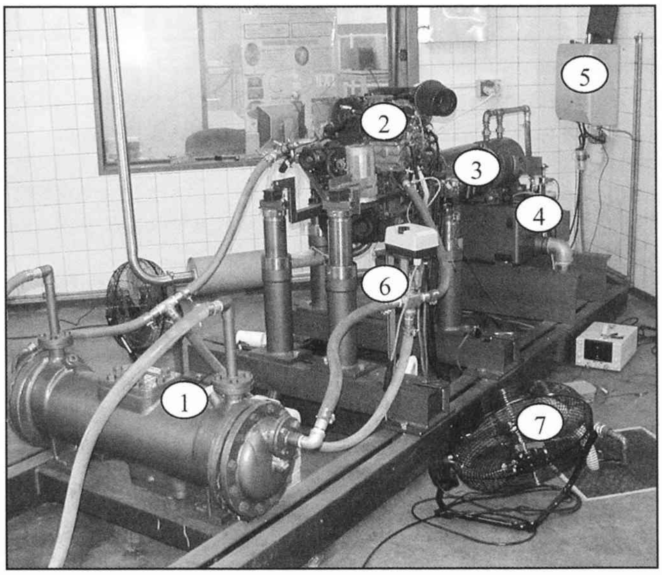

Figure 2: Test bed photo with labelled equipment

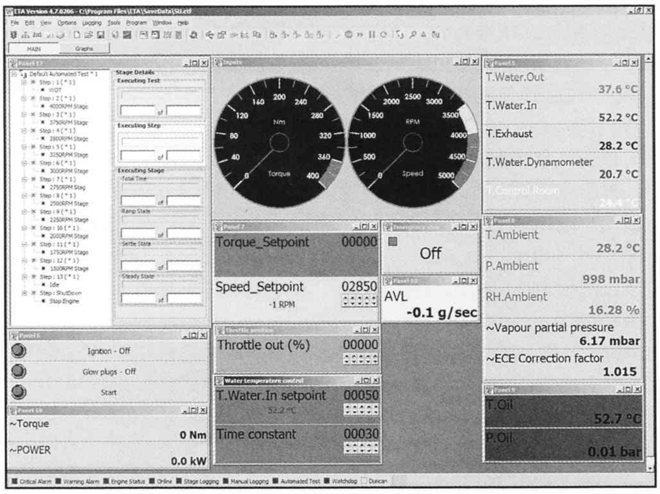

Figure 3: ETA's customized user interface

3.3 Experimental procedure

Before any tests are executed an inspection is done of the engine, test cell and equipment. The engine is then started and warmed up. When the engine operating temperature has been reached two consecutive performances curves are generated on mineral diesel. The final result is the average between the two curves.

The biodiesel used was not within the SANS 1935:2004 specification (see table 1). The parameters that greatly influence the use of biodiesel in combustion engines are: water content; viscosity; acid value; sulphated ash; free and total glycerol; flash point and calculated cetane index. Various blends of mineral diesel and biodiesel, from B5 to B100, were blended and tested

Analysis	Specification: SANS 1935:2004	Result
Appearance		Clear
Density @ 15 °C.kg/l	0.860-0.900	0.893
Viscosity @ 40°C	3.5-5.0	7.91
Flash point (°C)	120 min	fail
Calculated cetane index	51 min	49
Sulphated ash (%)	0.02 max	0.025
Water content (%)	0.05 max	0.08
Acid value (mg KOH/g)	0.5 max	0.78
Iodine value (mg I/g)	140 max	69.5
Free glycerol (%)	0.02 max	0.041
Total glycerol (%)	0.25 max	3.44

Table 1: Biodiesel test results

in a similar fashion to the mineral diesel. The fuel system is bled and re-primed between each test to ensure that it is clean.

4. Results and Discussion

4.1 Repeatability test

Ultra low sulphur diesel (ULSD) was tested before and after the biofuel mixtures to establish a base line and validate the tests by ensuring repeatability. The frictional force in the bearings of the dynamometer was determined to be the cause of small deviations between tests. The performance curve illustrating the repeatability is shown in figure 4, where ULSD1 was the initial run and ULSD2 the final run.

Similar to the power curves, the fuel consumption measurement from the AVL® fuel balance must also be checked for repeatability. The measurements from the before and after ULSD tests are plotted in figure 5. The two curves are similar, though not identical, with a maximum deviation of 0.324 g/s occurring at 4000 rpm. The might be attributed to the lack of fuel temperature control which still has to be implemented.

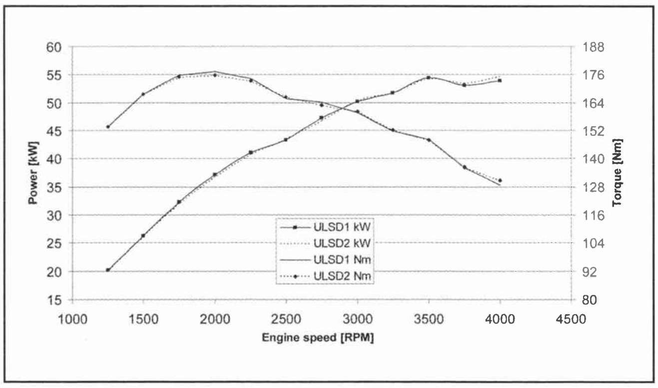

Figure 4: ULSD Performance curves showing repeatability

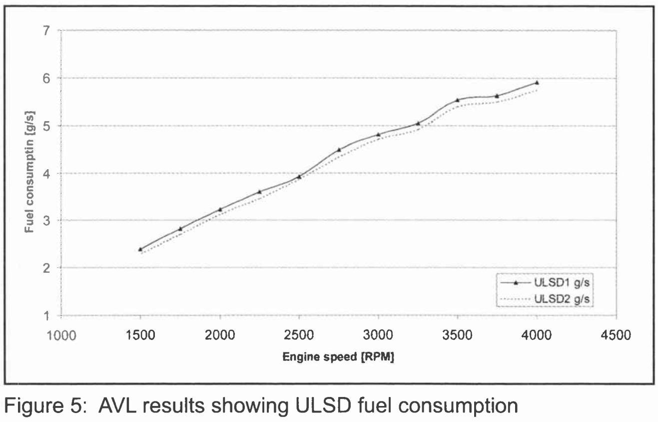

Figure 5: AVL results showing ULSD fuel consumption

4.2 Performance tests

The ULSD, biodiesel and its blends were tested and the power curve results plotted to graphically illustrate the performance differences of each fuel (figure 6). The dip in power at 3750 rpm was investigated and is a characteristic of the engine and not of the test facility. It can be seen that the fuels are similar in performance, although the engine produces slightly less power when operating on B100. The maximum difference between B100 and ULSD is 1.58 % at 3750 rpm and on average there is a 0.42 % decrease in power. Under normal driving conditions this would barely be noticeable, as it is a 0.85 kW power decrease, while a variation in ambient conditions such as temperature and altitude can be expected to have a bigger effect. Compression ignition (diesel) engines generally produce maximum torque between 1800 and 2100 rpm and for this particular engine it is around 1900 rpm. Figure 7 shows the test torque curves. The European Union 80/1269/EEC correction factor for turbo charged engines was applied during testing.

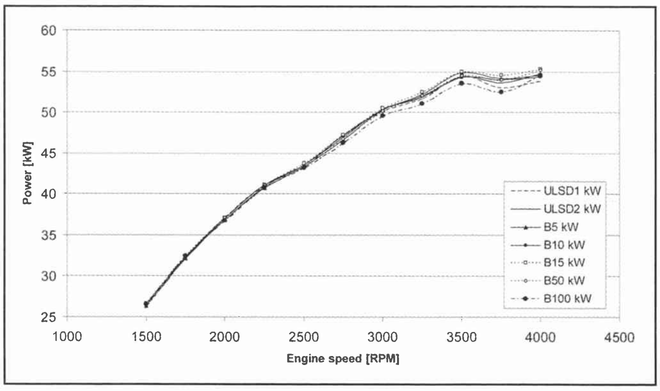

Figure 6: Power curves of ULSD, biodiesel and its blends

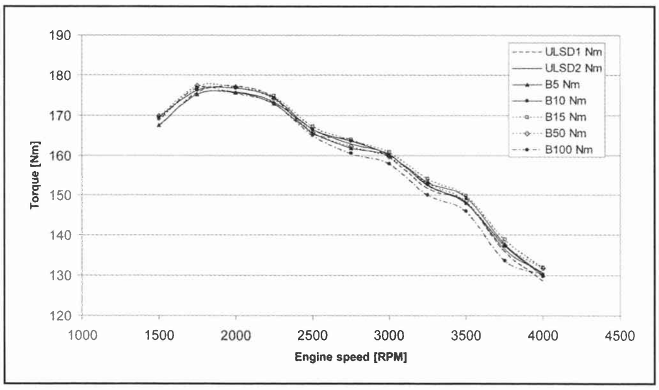

Figure 7: Torque curve for ULSD, biodiesel and its blends

The individual performance curve for B100 is plotted in figure 8. The power (kW) is plotted against the left hand side y-axis while the torque (Nm) is plotted against the right hand side y-axis.

All measured engine parameters, such as exhaust and oil temperatures, are approximately the same whether running on biodiesel or ULSD. For example at 2750 rpm (halfway through a test) the exhaust temperature for diesel and biodiesel are 757.8 °C and 753.2 °C, respectively. The 4.5 °C decrease is negligible. Similarly, the difference in coolant temperature is 0.1 °C, oil temperature is 0.2 °C and oil pressure is 0.1 bar. For practical purposes the results can be seen as being identical because they are within the tolerance of the sensors. Engine operating parameters thus stay the same when biodiesel or mineral diesel is used.

The fuel consumption results from the tests are plotted in figure 9. From the figure it can be seen that pure Biodiesel has the worst rate of fuel consumption, which improves as the mineral diesel:biodiesel ratio increases. This was expected since the energy content of biodiesel is lower than that of mineral diesel (see section 4.3). The lower blends, B5 to B15, have a minimal effect on the fuel consumption.

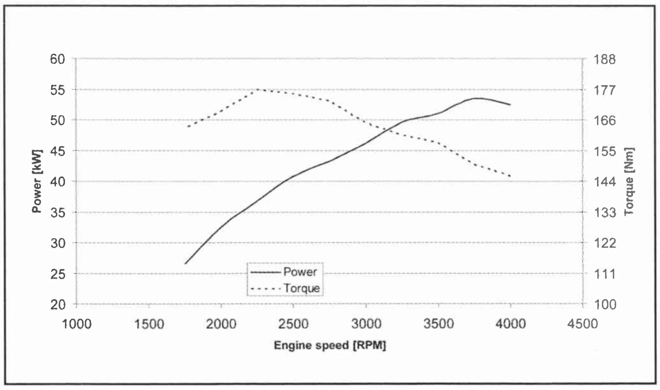

Figure 8: B100 performance curve

Brake specific fuel consumption is a measure of the engines thermal efficiency[6]. It can be assumed that the engine efficiency remains roughly constant throughout testing, thus the specific fuel consumption should also remain constant. This is indeed the case as illustrated in figure 10.

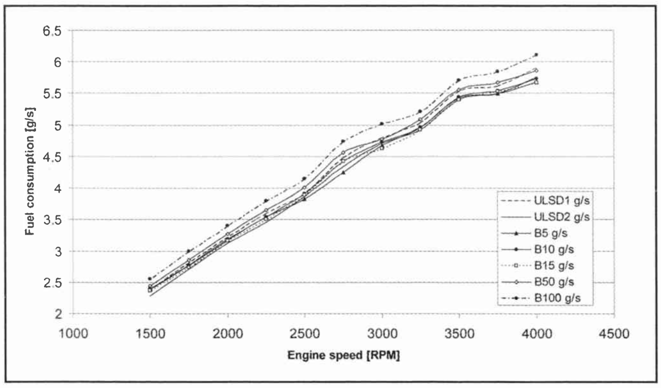

Figure 9: Fuel consumption rate curves for ULSD, biodiesel and its blends

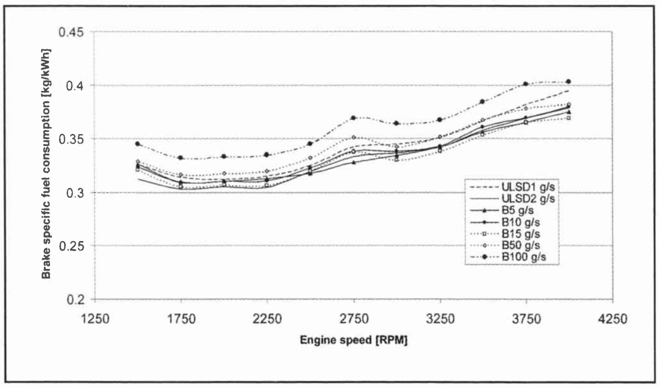

Figure 10: Brake specific fuel consumption in kg/kWh

4.3 Energy balance

An energy balance was used to determine the lower calorific value of biodiesel and as the final test cell validation method. If all the energy flowing into and out of the engine cannot be accounted for, it will indicate an error or incorrect calibration. The energy balance was calculated following the method described by Martyr and Plint[7].

The results from the test are shown in table 2. The energy balance for mineral diesel was calculated first, from which the calorific value of biodiesel could be determined. The lower calorific value for mineral diesel is on average 42.5 MJ/kg [6].

The calorific value for biodiesel was calculated using the convection and radiation energy losses calculated from the mineral diesel tests. The losses are assumed to be the same as the test setup did not change between the two fuel tests. The calculated calorific value for biodiesel (38.462 MJ/kg) is within 2.1 % of the calorie bomb test (39.336 MJ/kg). The thermal efficiency of the engine can then be calculated:

$$\eta_{Diesel} = 26.87\,\%$$

$$\eta_{Biodiesel} = 26.61\,\%$$

As can be seem from the thermal efficiencies there is no noticeable difference whether the engine is running on mineral diesel or biodiesel. This is to be expected as the thermal efficiency is an engine characteristic, and therefore independent of what fuel is used.

Parameter	Symbol	Results	
		Mineral diesel	Purebio diesel
Engine speed (rpm)		3000	3000
Power output (kW)	Ps	49.12	47.45
Fuel consumption rate (kg/s)	mf	0.0043	0.0046
Air consumption rate (kg/s)	ma	0.0657	0.0657
Lower calorific value (MJ/kg)	Cl	42.5	Calculated
Exhaust temperature (°C)	Tc	767.937	746.687
Coolant flow rate (kg/s) (°C)	mw	0.564	0.564
Coolant inlet temperature(°C)	T1w	47.57	47.94
Coolant outlet temperature(°C)	T2w	68.82	68.35
Inlet air temperature(°C)	Ta	21.81	21.81
Inlet air temperature(°C)	Ta	21.8	21.81

Table 2: Energy balance data[7]

The energy balance calculations are the final check that the test cell has been correctly calibrated. The engine is operating at a 26.87 % thermal efficiency which corresponds to the literature (25-30 %) for an engine of similar size. The losses to convection and radiation where calculated to be 13.56 %, which is also similar to values obtained from the literature[7].

5. Conclusion

- ❑ An engine test cell has been designed, built and commissioned and conforms to the traditional test cell layout.
- ❑ The test results are repeatable and accurate.
- ❑ Final validation of the test cell was performed by means of an energy balance. The lower calorific value for biodiesel was determined to be 38.5 MJ/kg.
- ❑ The unmodified engine ran successfully on biodiesel for the duration of testing.
- ❑ The fuel consumption using pure biodiesel was, as expected, higher than when using mineral diesel because of the lower energy content. Biodiesel blends show little or no consumption difference.

Note:
Please contact your vehicle manufacturer for guidelines on biodiesel operation before attempting a changeover. Only performance tests were carried out, long term reliability testing has yet to be performed.

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